Investigating the Influence of Specimen Size on the Uniaxial Compressive Strength and Elastic Modulus of Granite through Grain-Based Numerical Modeling

Marziyeh Moradi, Sasan Ghorbani*

Department of Mining Engineering, Hamedan University of Technology, Hamedan, Iran

ABSTRACT

The scale effect is considered one of the most significant factors governing the mechanical behavior of rocks. This study investigated the influence of the height-to-diameter ratio (H/D) and grain arrangement on the uniaxial compressive strength (UCS) and modulus of elasticity (E) of granite using finite element modeling. For this purpose, samples with three grain arrangements including irregular, medium regular, and almost regular were generated and simulated under uniaxial compression for H/D ratios of 0.8, 1.4, and 2. The results indicated that increasing the H/D ratio from 0.8 to 2 led to a reduction in average UCS values ranging from 17% to 26% across all grain structures. In contrast, the modulus of elasticity exhibited lower sensitivity to changes in sample dimensions, with a reduction ranging between 4% and 8%. The analysis of grain arrangement effects showed that disordered structures, with greater scatter in UCS values, exhibit the highest sensitivity to the scale effect, whereas more regular networks, due to a more uniform stress distribution, produce more mechanically stable behavior. To quantitatively analyze the scale effect, power relationships were derived between the mechanical parameters and the H/D ratio. The analyses indicated that the scale effect sensitivity coefficient for UCS is significantly higher than that for the modulus of elasticity; specifically, the ratio of the scale effect intensity of UCS to E (β_{UCS} / λ_E) in medium regular structures was estimated to be 4.9. This study showed that the scale effect of granite is mainly resistive and strongly controlled by microstructural heterogeneity and grain arrangement.

KEYWORDS

Microstructural heterogeneity, Height to diameter ratio, Uniaxial compressive strength, Scale-effect intensity, Modulus of elasticity

* Email: s.ghorbani@hut.ac.ir

1. Introduction

The investigation of size effects on the strength and deformability of rock masses has long been recognized as a fundamental topic in rock engineering. In particular, the dependence of the uniaxial compressive strength (UCS) and elastic modulus (E) on rock specimen dimensions plays a pivotal role in the design of rock structures [1]. Numerous studies have demonstrated that the UCS of intact rock decreases with increasing specimen size. This phenomenon is primarily attributed to the higher probability of pre-existing discontinuities and inherent defects being present within larger rock volumes. However, the exact nature of the size effect depends on several factors, including rock type, mineralogical composition, and porosity [2,3].

In recent years, various numerical methods have been extensively employed in rock mechanics. In general, both continuum and discontinuum approaches have been used to investigate the effects of grain size and specimen dimensions on the strength and elastic modulus of rocks. Among these, advanced techniques such as grain-based modeling (GBM) have attracted considerable attention. Grain-based modeling offers a high capability for representing the heterogeneous microstructural characteristics of rocks, including individual mineral grains and intergranular interactions [4].

Considering the significance of the size effect on the mechanical behavior of rocks and the role of microstructural heterogeneity in governing this phenomenon, the primary objective of this study is to investigate the effects of the specimen height-to-diameter ratio (H/D) and grain arrangement on the uniaxial compressive strength and elastic modulus of granite using grain-based numerical modeling.

2. Construction of the grain-based model and numerical simulation framework

In this study, the grain geometry was generated using the Voronoi tessellation technique to realistically represent the microstructure of granite. To investigate the influence of microstructural heterogeneity, three different grain arrangements, namely irregular, medium-regular, and almost regular structures, were generated. To evaluate the size effect, numerical specimens with three different height-to-diameter ratios of 0.8, 1.4, and 2 were generated (Fig. 1).

All numerical models were subjected to uniaxial compressive loading, which was applied incrementally until complete failure occurred. Upon completion of all simulations, the mechanical parameters, including stress-strain, UCS, and elastic modulus, were extracted.

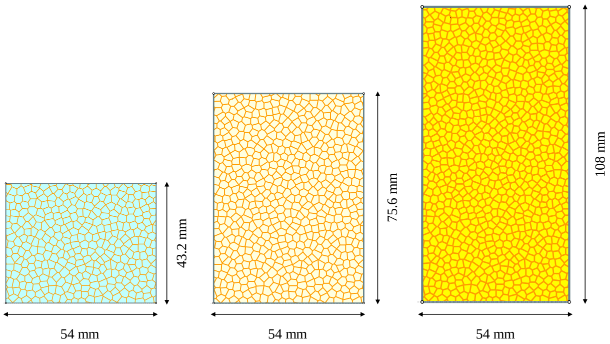
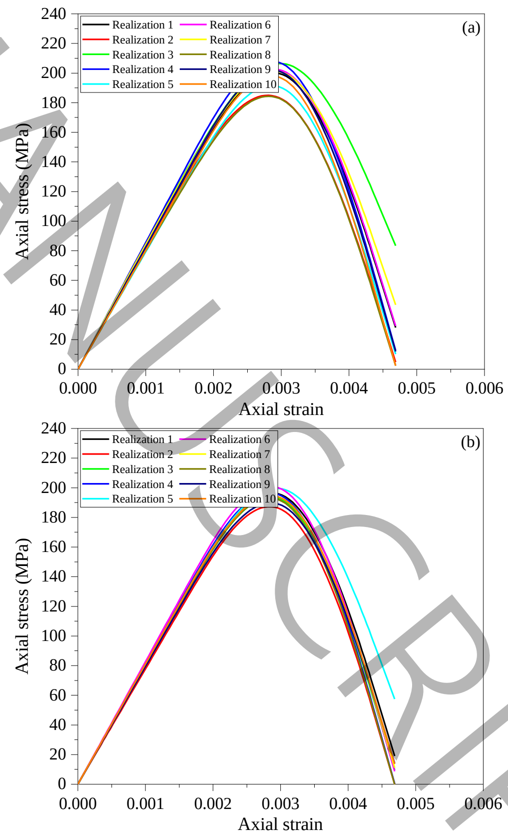


Figure 1. Some of the generated GBMs for different H/D ratios

3. Extraction of the uniaxial compressive strength and elastic modulus from the generated GBMs

Figure 2 presents the stress-strain curves obtained from the numerical simulations of granite specimens with an H/D ratio of 0.8 and various grain arrangements. These curves provide valuable information regarding the elastic behavior, damage initiation, crack propagation, load-bearing capacity, and failure mechanism of the specimens. In general, all curves exhibit the characteristic brittle behavior of granite under uniaxial compression, with an initially nearly linear elastic region followed by a sudden stress drop after reaching the peak stress.



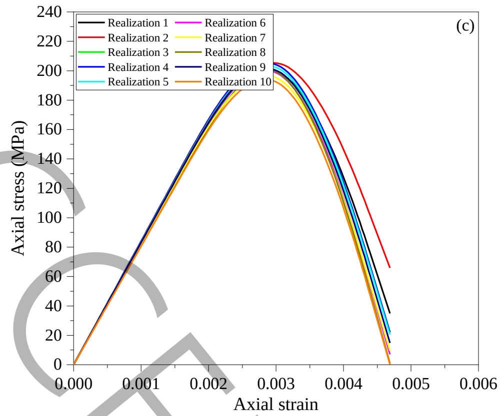


Fig. 2. Stress-strain curves of granite with H/D = 0.8 for (a) irregular networks, (b) medium-regular networks, and (c) almost-regular networks

4. Results and discussion

The statistical relationships between the H/D ratio and the mechanical properties of granite are presented in Figures 3 and 4. The obtained results clearly demonstrate that the specimen height-to-diameter ratio has a significant influence on the uniaxial compressive strength and, to a lesser extent, on the elastic modulus of the rock. As shown in Figure 3, the UCS exhibits a nonlinear decreasing trend with increasing H/D ratio for all grain structures. The greatest reduction in strength occurs over the H/D range from 0.8 to 1.4, whereas the rate of strength reduction decreases between H/D = 1.4 and 2.0.

Figure 4 also illustrates the relationship between the H/D ratio and the elastic modulus. Unlike the uniaxial compressive strength, the elastic modulus exhibits a weaker dependence on the size effect. Although a decreasing trend is observed with increasing H/D ratio, the variation in elastic modulus remains limited across all grain arrangements.

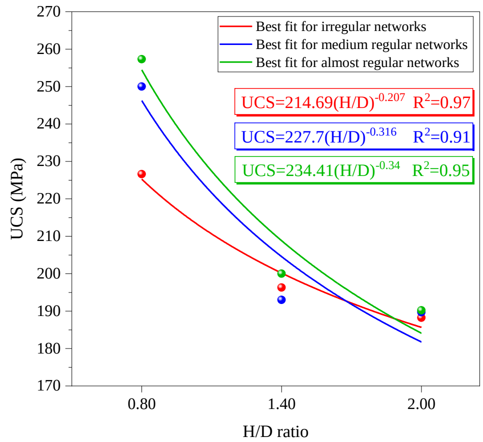


Fig. 3. Statistical relationship between the H/D ratio and the UCS of granite in networks with different arrangements

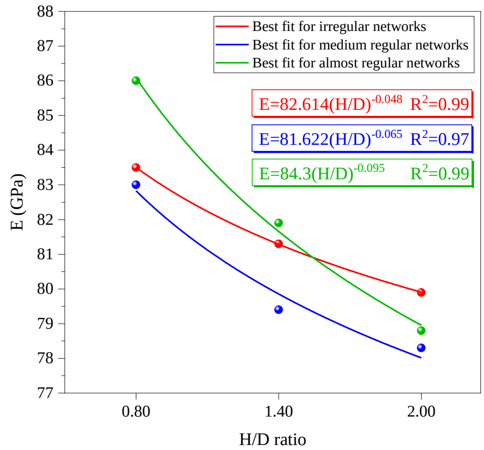


Fig. 4. Statistical relationship between the H/D ratio and the Young's modulus of granite in networks with different arrangements

5. Conclusion

In this study, the effect of the specimen height-to-diameter ratio on the uniaxial compressive strength and elastic modulus of granite was investigated using grain-based numerical modeling. Based on the analysis, the main findings of this study are summarized as follows:

- Overall, the results demonstrate that the size effect and microstructural heterogeneity are key factors governing the mechanical behavior of crystalline rocks and should be carefully considered in rock engineering analyses and the design of rock structures.
- The uniaxial compressive strength of granite decreased with increasing H/D ratio from 0.8 to 2.0 for all grain arrangements. The reductions for the irregular, medium-regular, and almost regular networks were 16.9%, 24.1%, and 26.0%, respectively.
- The greatest reduction in UCS was observed within the H/D range of 0.8-1.4 for the medium-regular and almost regular networks, whereas the magnitude of the size effect decreased for larger specimen dimensions.

6. References

[1] H. Masoumi, K.J. Douglas, A.R. Russell, A bounding surface plasticity model for intact rock exhibiting size-dependent behavior, Rock Mechanics and Rock Engineering, 49(2016) 47-62.

[2] R. Yoshinaka, M. Osada, H. Park, T. Sasaki, K. Sasaki, Practical determination of mechanical design parameters of intact rock considering scale effect, Engineering Geology, 96(2008) 173-186.

[3] B.A. Poulsen, D.P. Adhikary, A numerical study of the scale effect in coal strength, International Journal of Rock Mechanics & Mining Sciences, 63(2013) 62-71.

[4] S. Ghorbani, Effect of grain network structure on macroproperties and strain energy of marble under unconfined compression using 2D continuum based Voronoi models, Scientific Reports, 16(2026) 3727.